THE STRUCTURE OF ROTATING STRATIFIED FLOWS

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Abstract

Detailled 2D Particle traking and PIV visualizations performed on a series of large scale laboratory experiments at the Coriolis Platform of the SINTEF in Trondheim have revealed several resonances which scale on the Strouhal, the Rossby and the Richardson numbers. More than 100 experiments spanned a wide range of Rossby Deformation Radii and the topological structures (Parabolic /Eliptic /Hyperbolic) of the quasi-balanced stratified-rotating flows were studied when stirring (akin to coastal mixing) occured at a side of the tank. The strong asymetry favored by the total vorticity produces a wealth of mixing patterns. The basic aim is to study the structure of turbulent rotating fronts such as those created by the entrainment of a turbulent coastal mixing front in stratified environments. The stratification controlled by the local Reynolds and Strouhal numbers and by the local Richardson Number that may be either produced by a fresh water input such as that of a river or estuary or by an existing picnocline or thermocine. The external structure of the flow is parametrized by the Rossby number and by the Rossby deformation radius controlling the maximum stable two dimensional vortices. Experiments investigating a wide parameter space of Richardson and Rossby nubers by the rotation of an initially sharp density interface produced by brine set a model of the ocean conditions and the oscillation of a grid at the interface at one of the sides of the Trondheim Rotating Coriolis Platform set the conditions for coastal mixing.

The oceans receive energy inputs at a wide range of scales, the non-linear interactions that produce turbulent cascades, affect strongly the dispersion of both man-made pollutants and the natural biological tracers which exist in the ocean surface. The ability of the ERS-1/2 satellites to monitor a large area and the capabilities of the space-born Synthetic Aperture Radar SAR to detect the change of the sea surface roughness, allows the use of spatial remote sensing to identify the structure of the ocean vortices. These have been observed to be strongly influenced by the coastal mixing (Joly et al. 2000, Platonov 2001) The theory of the fractal analysis can be applicated to the determination of the natural or man-made origin due to the distinct self-similar of sea surface features in SAR imagery (Redondo and Linden, 1996) It is also possible to identify the sea surface structures of different origins in SAR imagery (Platonov 2002). The differences in multifractality are detected using the multifractal box counting algorithm on different sets of SAR images gives additional information on the structure of the turbulence in the ocean surface

Description of the experiments

The dynamical processes associated with the stably stratified atmospheric boundary layer or in the ocean thermocline are less well understood than those of its convective counterparts. This is due to its complexity, and the fact that buoyancy reduces entrainment across density interfaces. We present results on a series of laboratory experiments where a sharp density interface generated by either salt concentration
or heat, advances due to grid stirred turbulence.

This work presents the results of two laboratory experiments with a similar configuration shown in figure 1. The characteristic induced structures near the coast due to non homogeneous mixing were studied both with and without rotation Laboratory experiences were developed on a five meters turntable (SINTEF facilities) taking into account the Froude-Rossby similarities. While previously non rotating experiments were reported by Carrillo et al. (2001). This work evidences complementary results from the vortex characteristics and its forcing by either coastal induced shear or by the Rossby deformation radius. Additionally numerical models were compared with the laboratory models to investigate further the interaction between the small scale grid turbulence and the Rosby deformation radius.

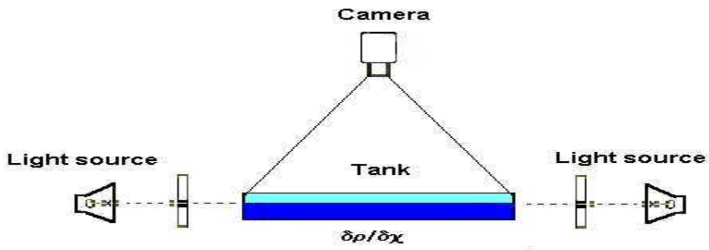


Figure 1. Experimenmtal set up

Experiments and non-dimensional parameters

Physical variables that describe mixing are compared with experimental laboratory results from a large number of studies of mixing dynamics in environmental fluids. Mixing descriptors such as Entrainment, Rossby number Richardson number and Reynolds number were employed as parameters. Mixing turbulence across a density interface generated by an oscillating grid inside a mixing-box was performed following Redondo(1990) The horizontal advance of a turbulent front in a stratified system with and without a lateral current, inside a 1 m x 1 m square box. were performed measuring the turbulentt components of velocity and using PIV and Particle tracking to detect the structure of the vortices and fronts. A larger experiment was set up in Trondheim at the Coriolis Platform with an experimental model in a 2 m x 4 m rectangular tank on a 5-m diameter turntable. The non rotating experiments were developed in the UPC applied physics laboratories in Barcelona, while most rotating experiments were performed in the SINTEF laboratories in Trondheim.

Particle tracking and optical measurements in the water column were used to study the induced length scale dynamics in the modelled coastal stirring. The dominant structures and scales from laboratory simulations were compared with the field data in (Carrillo et al 2001 and Carrillo 2002). Previous work Redondo(1990) used the Richardson number with the Reynolds number as a mixing descriptor, decribing the probability distribution of several basic instabilities such as internal waves, Holmboe or Kelvin-Helmholtz instabilities.

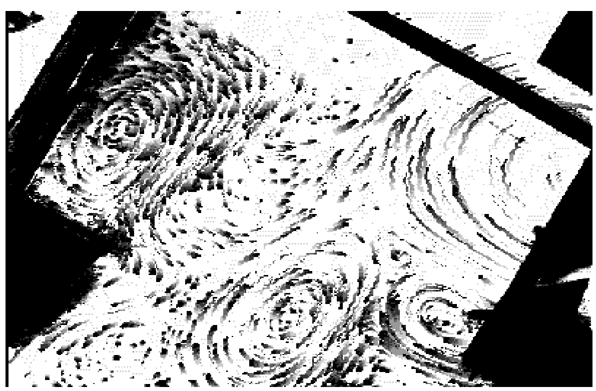
Advanced techniques of laboratory simulations, image processing and numerical modelling were compared in Carrillo et al. (2003) Experiments were used to describe the dynamics of the flow and the effects of buoyancy and Coriolis forcing. More than one hundred experiments were performed under quasy-steady conditions, which ment controling simultaniously the rotation induced accelerations and the mixing at the interface from the previously set density interface that had to be prepared carefully before the Coriolis platform was rotated, measuring the initial and final density profiles allow to compare mixing. The existing data-base, which has been filtered and preadjusted for PIV and particle tracking visualization. More than 20 hours of video of a seeding of pliolite sieved particles are available at present and a selection of the experiments were analysed with the DIGIMAGE and INMACALC fluid mechanics software packadges at the UPC Fluid Dynamics Laboratory. Related work of coastal induced dispersion produced by a river estuary have been performed and analysed, These experiments have recently been published for coastal jet stirring by Carrillo et al. (2001). and in particular a series of experiments performed at the Trondheim Coriolis where the coastal stirring was due to a surface jet modelling the Ebro estuary (which was compared with existing field observations and numerical models) has been recently published by Carrillo (2002). Most of the existing data analysed has been in the form of zenital video recordings which gives a clear predictive relationship between the value of the Rossby deformation radius, *Rd* and the size of the dominant vortices.

$$Rd = u' / 2\Omega\, l$$

We parametrize the level of buoyancy at the density interface by a local Richardson number defined in terms of the density difference across the interface, which may be due to a temperature or salinity jump. L is the integral lengthscale and u' is the r.m.s. velocity scale. So the relevant local Richardson number is $Ri = g \Delta\rho\, l / \rho\, u'^2$. The laboratory experiments were designed to compare the entrainment produced by zero-mean turbulence in heat or salt density interfaces. In the experiment we used the large tanks of either 1 or 8 m2 in base, a grid of mesh (M= 3.5 cm) placed at the side of the tank was driven by a motor. The density interface, genrated by disolving salt in the bottom layer of the water column and adding the top light layer, which had a pre set density difference, carefully by means of a sponge float.

The grid was set to oscillate with fixed frequency and stroke at the begining of the experiment and the velocity of advance of the turbulent front was measured by video recording the extent of the small scale stirring. The turbulent parameters are derived from previous measurements. The integral lengthscale is a function of the distance from the grid center and the front x as: l = 0.1 x and the turbulent velocity u´decays inversely proportional to the distance z. There are several mechanisms that produce mixing across the density interface and in general Entrainment may be dependent on the local Reynolds number, Re = u' l / ν the Rossby number and Richardson number, defined as functions of the r.m.s turbulent velocity and on the integral length scale of the turbulence . It is easy to deduce the lateral dependence of the basic parameters, which indicates the strong non-homogeneity of the mixing process Ri(x) = c x-1 , Ro(x) = c x-2 but Re(x) = cte. In the same experiment a region in parameter space is covered providing that Ri = c Ro1/2 .

When relating the Flux Richardson number to the Gradient one Boussinesq's relation between fluxes and gradients, allow to prescribe the eddy-viscosity and, more generally, all turbulence transport coeffi cients, such as thermal and mass diffusivities. This can be achieved algebraically, or by introducing one or more additional transport equations. Some such proposals have been reviewed by Chassaign(1996). In general a model such that Km= f(x, Ri, Ro, Re) provides accurate predictions. In figures 2 two very different flow patterns are seen and because the dominant eddies disperse much less than the shear regions. Topological criteria should also be used (Linden and Redondo 2002).



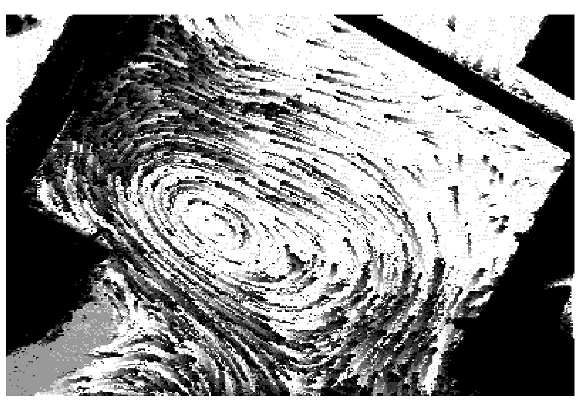


Figure 2. Streaklines of the flow (Low Ld above, high Ld below)

In studying the stratified rotating layers interacting with lateral non-homogeneous grid stirring the choice of a single characteristic length scale in the forcing is questionable. This can be seen from different results obtained in different regions of the parameter space in terms of the Richardson and the Rossby number, where the characteristic length scale of the dominant eddies range from the size of the forcing grid mesh to up to 20 times the grid mesh. The ranges of energy containing eddies also exhibits a dependence on the product of the Richardson and the Rossby number.

Experimental Results and Discussion

A selection of the experiments proyected regardless of the value of the Reynolds number spans almost three decades of the Richardson number and about two of the Rossby number. It is convenient to plot the inverse Rossby number in abcisae so that experiments in which Rotation and Stratification are roughly in balance (as is the case in most environmental fluids) ly close to the diagonal of figure 3. The points where the Richardson number is high (top-left) are dominated by buoyancy, while the points where the Rossby number is low (bottom-right) exhibit flow dominated by Coriolis forcing.

Fluid avection stretches blobs or clouds of scalar quantities so that their bounding surface stretches and increases in area. This growth of surface area is usually accompanied by folding of the surface, particularly when the advection occurs in a finite domain where stretched and advected material surfaces must fold in order for their increasing surface area to fit inside this finite domain.

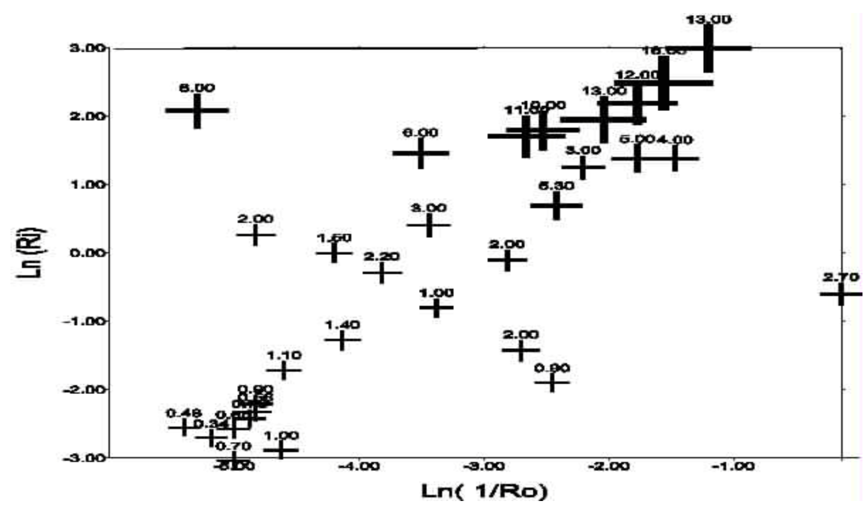


Figure 3. Parameter space showing the initial experimental values calculated at a distance of 10 grid meshes (M) from the wall. The numbers and size of the crosses indicate the value of the dominant eddies in non-dimensional form L/M.

The role of Stratification on mixing is fundamental as effective vertical diffusivities may span four orders of magnitude. The experiments of Turner (1968) showed however that molecular diffusivity values were able to affect the turbulent mixing. This perplexing cross-scale phenomenae may be explained in the subtle way in which the strech and fold mechanism is coupled with an internal wave field that in turn produces very oscillatory Lagrangian correlations, then even molecular effects may produce a multiplying effect on the overall mixing and Entrainment. The mixing ability in the reported experiments in stratified rotating flow will depend on both the Richardson and Rossby numbers.The entrainment is a power function of the local Richardson number, and the value of the empirical exponent *n(Ri,Pr)* is compared with previous results. The relationship between the Flux Richardson number and the Gradient or local one and the ways in which the interface extracts energy from the turbulence source via internal waves Internal gravity (or buoyancy) waves are characteristic of the stable boundary layer and contribute to its transport processes, both directly, and indirectly via internal wave-induced turbulence.

These proceses are able to control entrainment across strong density interfaces as those defined by Redondo(1989,1990) and would need to be added as a third coordinate Re in figure 3 A comparison of the range of entrainment values from laboratory experiments with those ocurring in nature, both in the atmosphere and ocean shows the importance of modeling correctly the integral lengthscales of the 2D turbulence, namely the Rossby deformation Radius. In the parameter space with high Ri and low Ro the dominant eddy sizes are large (more than 5 M) at the same time vorticity values are higher than shear ($\Omega_{ij} > S_{ij}$) Such differences between the simmetric and antisimetric parts of the deformation tensor are not evident for low Ri nor for large Ro.
For values near the origen, where the Reynolds number is also high, lenghtscales are smaller (of the order of M) and Shear dominates the velocity field. Related to dispersion the value of intermittency calculated in the usual way as the differences in scaling of the sixth order structure function also depends on Ri and Re.

Acknowledgments

A grant from the European Union under the TMR programme (HPRI-1999-CT00060)-Trondheim Marine Systems RI-Ref 200-266-471AN, is aknowledged as well as MCYT grant FTN2001-2220. Thanks are due to Dr. A. Carrillo and E. Perez for their work at SINTEF and to Prof. T. McClimmans for his hospitality.

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